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Lac Télé structure, Republic of Congo: Geological setting of a cryptozoological and biodiversity hotspot, and evidence against an impact origin

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ABSTRACT

Lac Télé is a large lake, ~5.6 km in diameter, with an ovoid shape, situated at 17°10′E, 1°20′N, in the great tropical rain forest region of the Republic of Congo. This lake has attracted widespread attention, mainly because of the legends among the local people that it harbours a strange animal known as the Mokele-Mbembe, but also because it is situated in a region that is a hotbed of biodiversity and conservation efforts with respect to various endangered mammalian species, including gorillas and chimpanzees. Because of its appearance, Lac Télé has been regarded as a possible meteorite impact structure. Various expeditions, studying cryptozoology, conservation ecology, biodiversity, and the impact hypothesis, have visited Lac Télé in the past several decades.

The Lac Télé structure is located in the NW part of the intracratonic Congo Basin, in a region dominated by Holocene alluvium, dense tropical rain forest, and swamps which form part of the basin of the Likouala aux Herbes, a multi-branched meandering river flowing over very low gradients into the Sangha river, a major tributary of the Congo river. Previous bathymetric studies have shown that the average depth of Lac Télé is only 4 m, including organic-rich silty sediments. The structure is that of a flat-bottomed dish.

Modelling of the Lac Télé as an impact structure indicates a number of features which ought to be present. The absence of any of these features, coupled with the irregular ovoid shape, the palynological record, and the location of the structure at the intersection of major regional lineaments, is regarded as evidence against the impact hypothesis.

Lac Télé as an isolated lake ecosystem is not unique in the Congo Basin, and there are several other similar small shallow isolated lakes surrounded by rain forest and marshes, some of which formed by damming of drainage systems by neotectonic faults. It is suggested that the formation of Lac Télé may be related to its location over neotectonically reactivated regional lineaments, which are also seismically active. Lac Télé and other similar hydrologic systems may be biodiversity hotspots because they acted as refugia following neotectonic hydrological re-organization of the Congo Basin.

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1. Introduction

Of the great tropical rain forest regions, the northwestern part of the Congo Basin in central Africa is one of the largest and least known. Within this vast region, covering over 220,000 km^2 of forested swampland (Burgis and Symoens, 1987), there is a large lake which has an almost perfectly regular ovoid shape, called Lac Télé, having a long dimension of 6.4 km, which is situated at 17°10′E, 1°20′N (Figs. 1–3).

The rain forest of the Congo Basin is one of the last remaining tropical wildernesses in the world, and is a top priority for biodiversity conservation (Kamdem-Toham et al., 2003). The region around Lac Télé harbours several critically endangered large mammal species such as the forest elephants *Loxodonta africana cyclotis*, the western lowland gorillas *Gorilla gorilla gorilla*, and common chimpanzees *Pan troglodytes troglodytes* (Lobel et al., 1989; Fay et al., 1989; Stokes et al., 2010). Recently, some large populations of western lowland gorillas have been discovered around Lac Télé (Rainey et al., 2010), and several new bonobo populations have been found around Lac Tumba (Inogwambi et al., 2010). The rich biodiversity in the region around Lac Télé and the Likouala aux Herbes swamps makes this a prime area for conservation in the Congo Basin, which is under increasing threat from logging (Blake, 1993; Wilkie et al., 2000; Laporte et al., 2007). Since 1991, the Wildlife Conservation Society, in collaboration with the Government of Congo and other partners, has established three major site-based conservation, and wildlife and natural resource management, projects across the Ndoki-Likouala landscape of the northern Republic of Congo. These are: (1) the Nouabalé-Ndoki National Park (NNNP), (2) the swamp forests of the Lac Télé Community Reserve (LTCR), and (3) Forestry Management Units (FMU) surrounding commercial logging concessions (Stokes et al., 2010) (Fig. 4).

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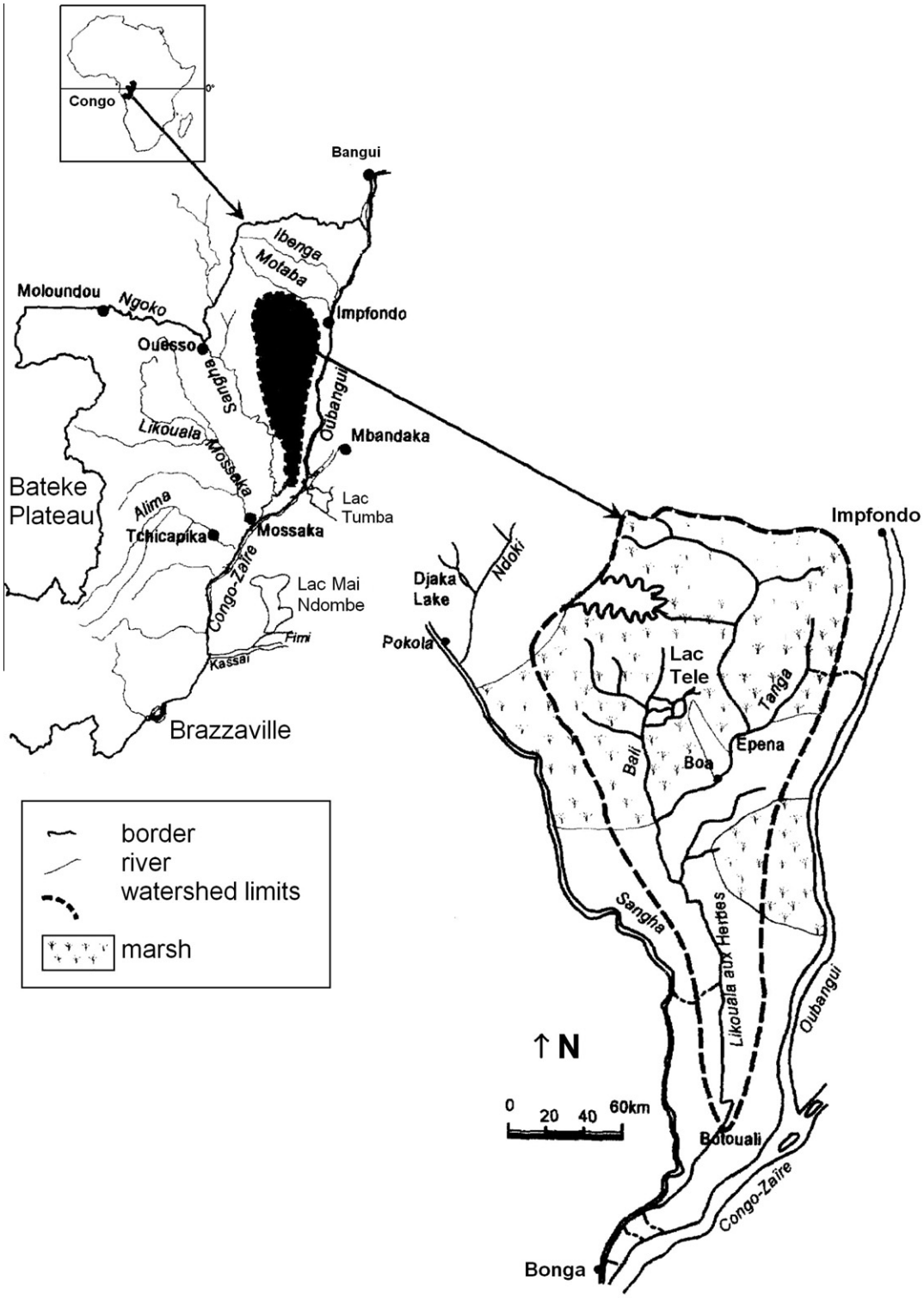

Fig. 1. Locality map of the Lac Télé structure, in relation to the drainage basin of the Likouala aux Herbes (dashed line), situated between the Sangha and Oubangui rivers. Insets show the Republic of Congo, and its location in Africa. After Laraque et al. (1998).

Lac Télé has attracted the attention of many curious people, mainly because of the legends among the local people that it harbours a strange animal known as the Mokele-Mbembe. Various expeditions, both by scientists and by lay adventurers, have visited Lac Télé in the past several decades (Heuvelmans, 1958, 1980; Grandin, 1976; Anon., 1981; Regusters, 1982; Mackal et al., 1982; Agnagna, 1983; ISC, 1986; Mackal, 1987; Nugent, 1993; O'Hanlon, 1996; Laraque et al., 1997, 1998; Ndanga, 2000; Quammen, 2000; Martin and Menvielle, 2004; Gibbons, 2009; Anon., 2010). None of the expeditions in search of the Mokele-Mbembe met with any success, although some claim to have sighted the creature (Regusters, 1982; Mackal et al., 1982; Agnagna, 1983).

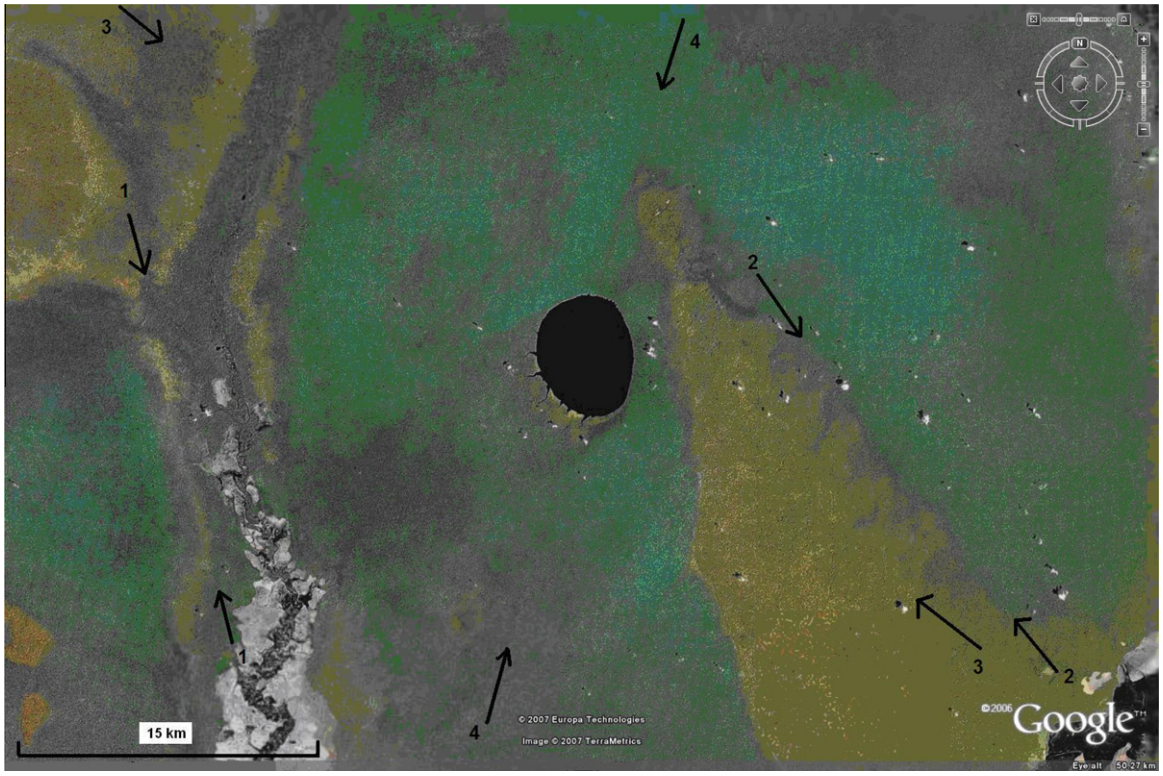

Fig. 2. Satellite image (from Google Earth) of Lac Télé (centre), with southwesterly drainage into the Likouala aux Herbes River (bottom left). The region shown in this image consists mainly of dense tropical rain forest and swampland. Linear features are shown by numbered pairs of arrows pointing to each other. Some lineaments are obvious structural features, such as the one subparallel to the Likouala aux Herbes river (1), and the NNW–SSE-trending lineament on the right hand side of the image (2). Other lineaments, such as the NNE–SSW-trending lineament (3), and the NE–SW lineament (4), going through Lac Télé, are less obvious, but may represent the surface expression of deep seated structures.

Fig. 3. Close-up satellite image of Lac Télé, courtesy of Google Earth.

Others claim that the creature is a reptile, akin to a sauropod dinosaur, that somehow continues to survive in the jungles of the Congo Basin (Heuvelmans, 1980; Mackal, 1987; Nugent, 1993; Shuker, 1995; Emmer, 2009). The legend of the

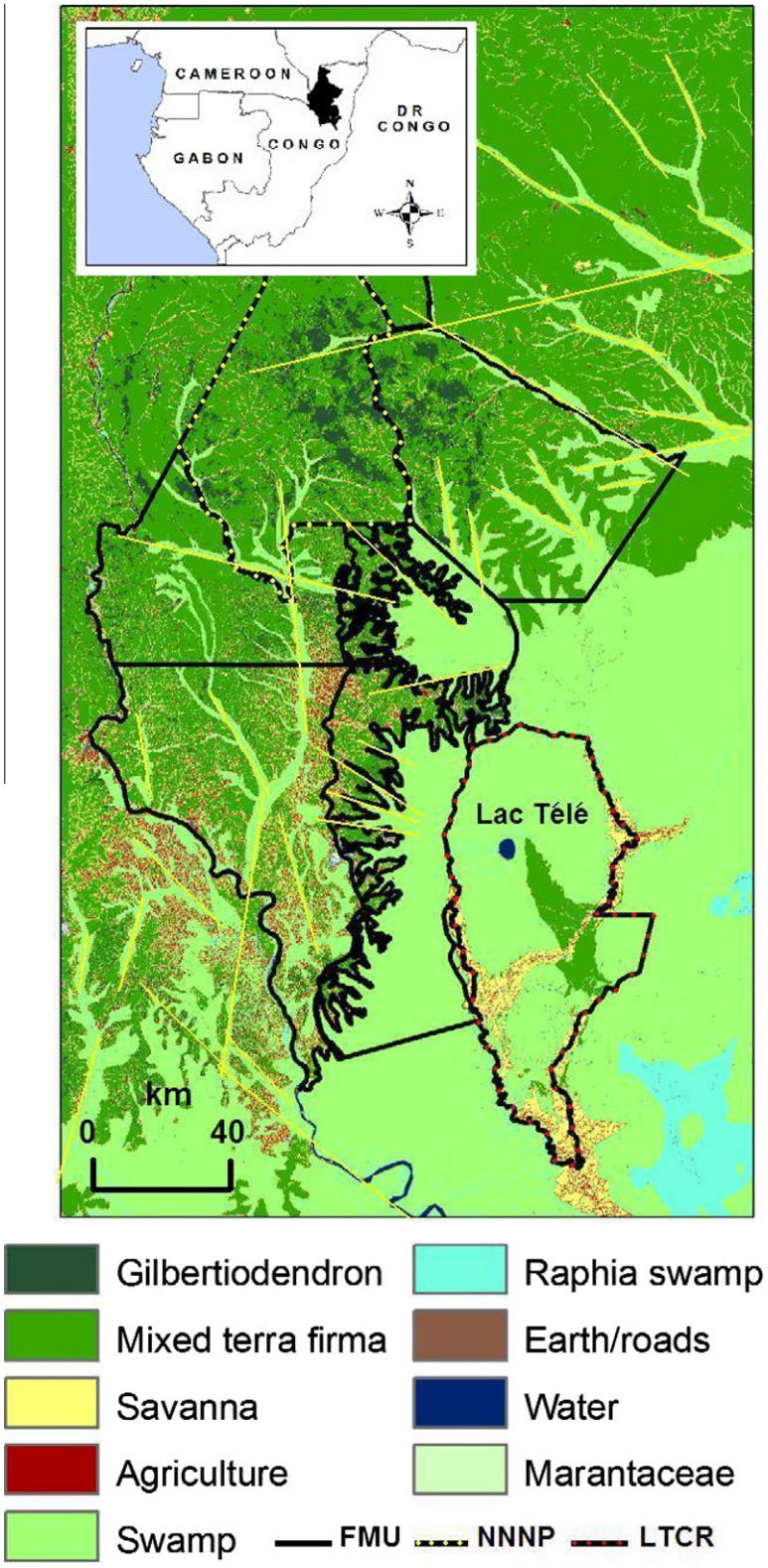

Fig. 4. The Ndoki-Likouala Conservation Landscape of northern Congo (after Stokes et al., 2010), showing main vegetation types. Structural lineaments based on straight river segments are shown in yellow. FMU = Forestry Management Units; NNNP = Nouabalé-Ndoki National Park; LTCR = Lac Télé Conservation Region. The inset is a locality map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mokele-Mbembe has also stirred the writer's imagination, and has resulted in at least five popular novels (Kunkel, 1955; Blish, 1962; Kelly, 1994; Smith, 2004; Thiemeyer, 2007). The National Geographic Society commissioned an expedition to Lac Télé in 2005 led by Dr. Brady Barr to study its snakes (Duane, 2005)- this led to the broadcast in May 2006 of a documentary entitled "Super Snake". Because of these legends, Lac Télé is regarded as a "hotspot" for cryptozoology, and ranks with several other sites

worldwide in the interest it has generated in the search (scientific or otherwise) for cryptic or mythical creatures.

Because of its appearance, Lac Télé has been regarded as a possible meteorite impact structure (Garvin, 1986); however, no corroborating evidence was presented to support this idea. If the lake is of impact origin, then, considering the age of the rain forest around it, it would have to be almost certainly of Quaternary, and most probably of Holocene, age- making it the third largest Quaternary terrestrial impact structure (after Zhamanshin and Bosumtwi), and the largest known Holocene structure. Hence the question of whether it is of impact origin or not is an important one for determining the frequency and magnitude of large impacts, and for assessing their threat to human society.

Impact structures produced by asteroid and comet impacts are common on planetary surfaces, but rare on the Earth because they are destroyed by erosion or tectonism, or buried, in the dynamic surface environment. Around 176 impact structures, ranging in age from Palaeoproterozoic to Recent have been discovered on Earth, and new structures are discovered every year (Grieve and Kring, 2007; Earth Impact Database, 2010). Many more circular features that are regarded as possible impact structures have been found, but they await confirmation of an impact origin from macroscopic and microscopic shock features, and associated meteoritic fragments (e.g., French, 1998; French and Koeberl, 2010). Recently there has been a resurgence of interest in young impact structures, because their frequency and size distribution has a direct bearing on the hazard to human society from impacts by asteroids and comets (Bobrowsky and Rickmann, 2007). A recent assessment of the Quaternary impact record indicates that there may have been more impacts than was generally believed from modelling based on the observed frequency and size distribution of Near-Earth Objects, such as asteroids and cometary fragments (Masse, 2007). The discovery in space and subsequent impact of asteroid 2008 TC_3 in the Nubian Desert of northern Sudan in October 2008, and the recovery of fragments of the asteroid, known as the Almahatta Sitta meteorite (Jenniskens et al., 2009), has added greatly to public interest in the impact hazard of Near-Earth Objects, and in the recent impact cratering record.

In maps and tables showing the global distribution of impact structures, there is an almost complete absence of known impact structures in the tropics (Grieve and Shoemaker, 1994; Grieve and Kring, 2007), with the exception of the Itturalde structure in the Amazon jungle of the Bolivian lowlands (Campbell et al., 1988). This is almost certainly due to non-discovery rather than non-occurrence of impact structures in the tropical regions, since impacts occur randomly on the Earth's surface. The high rates of rainfall and weathering in the tropics, coupled with dense rain forest and widespread cloud cover, make the tropical regions some of the least explored and least accessible in the world. In tropical Africa, there is only one confirmed impact structure (Bosumtwi in Ghana; Koeberl et al., 2007), and several possible structures which have yet to be proven to be of impact origin (Antoine et al., 2000; Master and Reimold, 2000; Reimold et al., 2001; Master, 2001; Master et al., 2001; Wade et al., 2006; Monegato et al., 2010).

Few of the previous expeditions to Lac Télé have investigated the physical environment and milieu of the lake itself. The only expedition that tried to investigate the possible impact origin of the Lac Télé structure was the 1996 expedition of Laraque and his colleagues (Laraque et al., 1997). They investigated samples for spherules (similar to those found from the central African Republic by Censier et al., 1992), and analysed them for Ir, in the hope of detecting cosmogenic Ir derived from a possible meteoritic impactor. However, their results were negative, and no sample yielded values above the detection limit (Laraque et al., 1998). No other work was done, and no other evidence was presented, to support this hypothesis; nevertheless, Laraque et al. (1998) suggested that perhaps the structure was the result of an airburst similar to that which accompanied the Tunguska event in Siberia in 1908, and they pointed out the absence of iridium anomalies associated with that event. Thus although the Lac Télé structure is of interest to the cryptozoological, biodiversity conservation, and impact cratering communities, the question of its origin still remains open.

2. Regional geological setting

The Lac Télé structure is situated within the northwestern part of the Congo Basin (also known in French as the Cuvette du Congo). The Congo Basin is a large intracratonic basin consisting of Phanerozoic sedimentary rocks, which overlies a basement of Archaean granite-greenstone terrains and high-grade gneisses, the Mesoproterozoic Kibaran belt, and several Neoproterozoic belts and basins (Veatch, 1935; Lepersonne, 1978). In the 1950s, there were a number of large geophysical surveys, including refraction seismics and gravity, which were conducted over the central Congo Basin, in what was then the Belgian Congo (now the Democratic Republic of Congo) (Evrard, 1954, 1957, 1960; Evrard and van Weelden, 1959). The results of these surveys indicated that the Congo Basin had two depocentres which were separated by a NW–SE-trending ridge or horst block (Evrard and van Weelden, 1959; Verbeek, 1962). More detailed seismic work was done in the central part of the Congo Basin by oil companies in the 1980s, and their results confimed the presence of the NW–SE-trending ridge, which was interpreted by Daly et al. (1991, 1992) to have formed as a result of far-field stresses due to Neoproterozoic collisions around the Congo Craton. The two depocentres in the Congo Basin, discovered from seismic work, were drilled in the mid 1950s, and the cores recovered from these two drillholes, the Samba and Dekese holes, were logged and studied in great detail by Cahen et al. (1959, 1960). Further deep exploration in the Congo Basin was done by oil companies in the 1980s, when two boreholes, the Mbandaka and Gilson Wells, were drilled (Daly et al., 1991, 1992).

The stratigraphy encountered in the three deepest cores, drilled to depths of 4350 m (Mbandaka), 2038 m (Samba) and 1856 m (Dekese), which intersected the deepest parts of the Congo Basin, indicates that the basin fill consists of a Phanerozoic sedimentary rock succession, ranging in age from early Palaeozoic to late Mesozoic and Pliocene to Holocene, which unconformably overlies a Neoproterozoic carbonate sequence (Cahen et al., 1959, 1960; Lawrence and Mvumbi, 1988; Daly et al., 1991, 1992; Kadima et al., 2009). The Late Jurassic to Cretaceous succession shows a marine interval with fish fauna, produced by epeirogenic movements which led to an incursion of the proto-Indian Ocean into the mainly continental Congo Basin from the NE (Sahagian, 1988; Doucouré and de Wit, 2003). The crystalline or metamorphic basement which underlies the basin is unknown, but probably includes Archaean rocks of the Kasai craton in the SE, the Northern Congo craton in the N, and the Massif du Chaillu in the W (Cahen et al., 1976), and Mesoproterozoic rocks of the Kibaran Belt in the NE and NW (Vicat et al., 1997; Master, 2004).

The southern third of the Congo Basin is dominated by outcrops of Cretaceous rocks, while Triassic to Jurassic (i.e., Karoo) rocks are found in the E and SW. The Bateke Plateau of the central part of the Republic of Congo, shows both marine and continental Mesozoic to Cenozoic successions which underlie the Quaternary to Recent alluvium of the NW Congo Basin (Nicolini and Roger, 1951; Le Marchal, 1966; Dadet, 1969; Giresse, 1982, 2005; Desthieux, 1993, 1995). The NW part of the Congo Basin is a region of Holocene alluvium, swamps, and dense tropical jungle (Dadet, 1969; Samba-Kimbata, 1991; Desthieux, 1993; Chadwick, 1995; Laporte

et al., 1998; Campbell, 2005; Lindquist et al., 2008). The tropical forest ecosystem has persisted in the Congo Basin since the beginning of the Holocene (Maley, 1996). The southwestern part of the Bateke Plateau marks a transition into savannah, and climatic fluctuations over the past five millenia have allowed encroachment of grasslands into forested regions during drier periods such as at 3000–2500 yr B.P. (Vincens et al., 1997), and at 1100–800 yr B.P. (Ngomanda et al., 2007). The Congo Basin has large surface and groundwater resources, which show significant seasonal and long-term fluctuations in storage capacity, as revealed by remote sensing studies (Rosenqvist and Birkett, 2002; Crowley et al., 2006; Bwangoy et al., 2010; Jung et al., 2010).

The region around Lac Télé, in the northwestern part of the Congo Basin, which lies in the Republic of Congo (i.e., Congo Brazzaville) has been very poorly studied. An aeromagnetic survey of this part of the basin (Hydro-Congo, 1981, cited in Desthieux et al., 1993) showed that the NW–SE-trending horst identified in the central Congo Basin (Verbeek, 1962) continues into the NW Congo Basin, where it is known as the Sangha Horst (Desthieux, 1993). The Sangha Horst separates the Impfondo Basin in the north from the Liranga Basin in the south. Although this horst does not show up in the surface geology of the NW Congo Basin, there are numerous NW–SE-trending lineaments parallel to the horst, which are defined by straight river segments (Desthieux, 1995). Lac Télé lies along one of these lineaments, which was mapped 50 km northwest of the lake (Desthieux, 1995). In the Batéké Plateau in the SW part of the Congo Basin in central Congo Republic, there are numerous NE-trending structurally-controlled straight river segments (e.g., on the Nkeni, Mpama and Alima rivers, all tributaries of the Congo river), along which the Neogene cover has been eroded away, exposing underlying Neoproterozoic rocks of the Stanley Pool Formation (Desthieux, 1995). The largest of these lineaments extends for 350 km, from north of Kayes in southern Congo to just south of Owando in central Congo. The northeastern continuation of the structural trend of the Kayes-Owando lineament has been recognised in the Hydro-Congo (1981) aeromagnetic survey as a fault which bounds the Owando depression, and continues northeast across the Sangha Horst, into the Impfondo Basin (Desthieux, 1993). The lineament emerges from underneath the Holocene alluvium in the northeasternmost corner of Congo, where it traverses Cretaceous sandstones of the Carnot Formation (Desthieux, 1995). Lac Télé appears to lie close to the intersection of one of the NW–SE-trending lineaments that parallel the Sangha Horst, and the northward continuation of the NE–SW Kayes-Owando lineament, where it is covered by the Holocene alluvium and swamps of the northeastern Congo Basin (Figs. 2 and 4).

There are no recorded young igneous rocks in the Congo Basin. The nearest Quaternary to Holocene igneous activity is at Mount Cameroon and other volcanoes of the Cameroon Volcanic Line, situated some 950 km west-northwest to northwest of Lac Télé; and the Virunga volcanoes of the Western Rift, about 1250 km to the east. Alluvial diamonds, which are known throughout the Congo, are thought to originate from kimberlites or other alkaline ultrabasic intrusions, although none have yet been identified in the Republic of Congo (Martini et al., 1995).

3. Lac Télé structure

The Lac Télé structure has an ovoid shape, with one side slightly flatter than the opposite side, resulting in an egg-shape. It has a NNE–SSW-trending semi-major axis 6.4 km long, and a WSW–ESE-trending semi-minor axis 4.8 km long (Laraque et al., 1997, 1998). Its shape is somewhere between that of a circle and an ellipse, and it is not exactly symmetrical about the long semi-major axis, nor about the semi-minor axis. The axial ratio (semi-major axis/semi-minor axis) is 1.33. The lake is surrounded by dense vegetation and swamps which form part of the basin of the Likouala aux Herbes river, a convolutedly anastomosing, multi-branched meandering river flowing over very low gradients into the Sangha river, a major tributary of the Congo river (Samba-Kimbata, 1991; Censier et al., 1995; Laraque et al., 1997, 1998). Issuing from the southwestern quadrant of Lac Télé are seven small distributary channels, which join with the Likouala aux Herbes some 15 km to the SW (Figs. 2, 3 and 5). A solitary channel enters the lake from the north. Thus the lake serves as a temporary reservoir in the drainage basin of the Likouala aux Herbes, In the datasets examined (including satellite imagery, Fig. 3; an oblique aerial photograph, Fig. 5, and images taken at lake level), there is absolutely no evidence of a topographically elevated rim around Lac Télé. The channels issuing from the lake merge with the surrounding swamps, and are called “molibos” by the Bangombe pygmies, who live around the lake (Gibbons, 2009).

Bathymetric studies by Grandin (1976) and Laraque et al. (1997, 1998) have shown that the average depth of Lac Télé is only 4 m, including organic-rich silty sediments (Fig. 6), with the surrounding Quaternary sedimentary rocks being undisturbed.

Fig. 5. Oblique aerial photograph of Lac Télé, looking northeast, showing several distributary channels on the bottom right, which feed into the Likouala aux Herbes river. Photograph by Michael Nichols, from Quammen (2000).

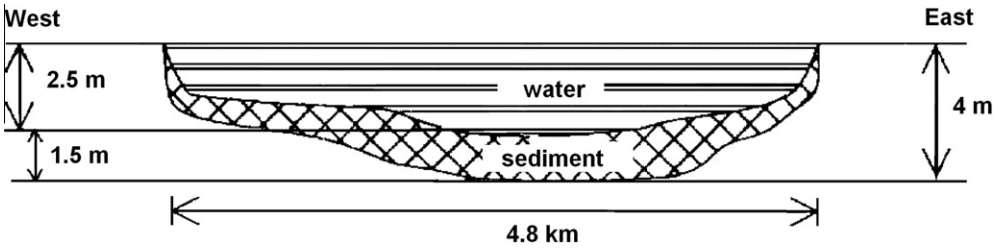

Fig. 6. North–south cross-section through Lac Télé (redrawn from Laraque et al. (1998)).

The sediments are highly organic-rich, and are composed of plant fibres, kaolinite and mixed-layer clays, together with some quartz, goethite, ilmenite and magnetite, and organic detritus, including siliceous sponge spicules (Laraque et al., 1998). The sediment fill is 1–1.5 m thick, overlain by a water column on average about 2.5 m deep (Laraque et al., 1997, 1998). The structure is that of a flat-bottomed dish. The area of the lake is 23 km^2; the total volume of the lake is 7.1×10^7 m^3; the volume of the water is 4.3×10^7 m^3, and the volume of the sediments is 2.8×10^7 m^3 (Laraque et al., 1997, 1998). The lacustrine sediments have an age >6600 yrs BP, based on a radiocarbon date from the bottom of a 1 metre sediment core from the lake (Laraque et al., 1997, 1998).

4. The origin of Lac Télé: discussion

Garvin (1986) and Laraque et al. (1997, 1998) postulated an impact origin for Lac Télé. No supporting evidence was given for this hypothesis. Laraque et al. (1998) found no evidence for any Ir anomaly (due to a possible extra-terrestrial impactor) in the lake sediments that they examined. They nevertheless postulated that the structure could have been produced by a Tunguska-type airburst produced by an exploding bolide. However, unlike the Tunguska region, where an area of 2150 ± 50 km^2 was devastated, and 80 million trees were flattened (Longo, 2007), there is no indication whatever that any trees were flattened or damaged at Lac Télé and the surrounding region. The photographs of the shoreline by Duane (2005) show a luxuriant abundance of old-growth vegetation, with no evidence for regrowth of a depauperate ecosystem, as would be expected if the region had undergone a recent Tunguska-type catastrophe. The absence of vegetation anomalies on the lakeshore does not, however, rule out such a catastrophe in the past, since vegetation can recover fairly quickly in a tropical environment. However, palynological studies (Laraque et al., 1997, 1998) also fail to show any change in the vegetation history in the past several thousand years (see below).

Assuming an impact origin of the Lac Télé structure allows us to calculate a few likely consequential environmental effects that should have affected the surrounding area, utilizing the arguments and computer program developed by Collins et al. (2005). If we assume the most likely impact angle (45°), the most likely impactor composition and density (asteroid with density of 3000 kg m^{-3}), and a typical impactor velocity of 17 km s^{-1}, we can estimate that a bolide of diameter 350 m will produce a final impact crater with a diameter of 5.6 km, corresponding roughly to the size of Lac Télé. Such a crater would have a final depth of about 500 m, and will be a complex crater with a central uplift. At a distance of 10 km from the impact site, more than 90% of the trees would have been blown down by the airblast from the impact, and the remainder would have been stripped of their leaves; the trees and grass would have been burnt by thermal radiation from the impact fireball, and shortly thereafter the ground would have been buried under 4 m of impact ejecta material. At a radius of 2.815 km from the impact site (i.e., just beyond the rim of the 5.6 km diameter impact structure), the continuous ejecta blanket would be 178 m thick.

Given the modelled consequences of a c. 5.6 km diameter impact structure, the actual situation of the similarly-sized Lac Télé structure differs in many fundamental aspects. The following points are argued as evidence *against* an impact origin for the Lac Télé structure:

(1) Ovoid shape. Impact structures are usually circular or polygonal in outline. The only oval-shaped structures are produced by very rare oblique impacts where the angle of incidence <5°, but in these the degree of obliquity (semi-major axis/semi-minor axis) of the impact ellipse is much higher than that in Lac Télé (1.33). For example, in the Rio Cuarto crater field in Argentina, regarded as having been produced by a grazing impact, the individual crater scars are extremely elongate, and do more resemble the shapes of cigars than of eggs (Schultz and Lianza, 1992).

(2) Shallow structure. In most impact structures, the depth of excavation is related to the diameter, such that for a crater of 5 km diameter, a depth of 500 m is expected (Melosh, 1989; Collins et al., 2005). Only in very oblique impacts is the depth of excavation much shallower. However, in such oblique impacts, the depth of excavation is still very much greater than in the Lac Télé structure, where the ratio of depth to average diameter is only 0.0007.

(3) Lack of topographically elevated, overturned rim. The centrifugal drainage from the Lac Télé indicates the lack of an elevated overturned rim around the structure. An elevated rim is a mechanical consequence of the impact cratering process (Melosh, 1989; Collins et al., 2005), and its lack argues against this process having operated in the creation of the Lac Télé structure. Even relatively tiny impact craters in marshland, such as the Kaali craters of Estonia, where the largest crater has a diameter of 110 m, have rims with appreciable relief of ~10 m (Veski et al., 2007).

(4) Lack of ejecta blanket. An impact crater if this size should have been surrounded by an eject blanket of material excavated and thrown out of the crater during an impact. Calculations indicate that such a blanket should have been about 178 m at the rim of the crater, and up to 4 m thick at a radial distance of 10 km from the centre of the structure. No evidence for such a blanket or its eroded remnants can be seen around Lac Télé.

(5) Lack of central uplift. The bathymetric results of Grandin (1976) and Laraque et al. (1997, 1998) indicate a shallow flat-bottomed basinal shape and lack of central uplift. For a crater of this size, in sedimentary country rocks, a central uplift should be present, from the mechanics of impact cratering (Melosh and Ivanov, 1999). For layered sedimentary targets, central uplifts start to form in craters with diameters of 2 km or more (Melosh, 1989). It should be noted that some large impact structures such as Bosumtwi (10.5 km

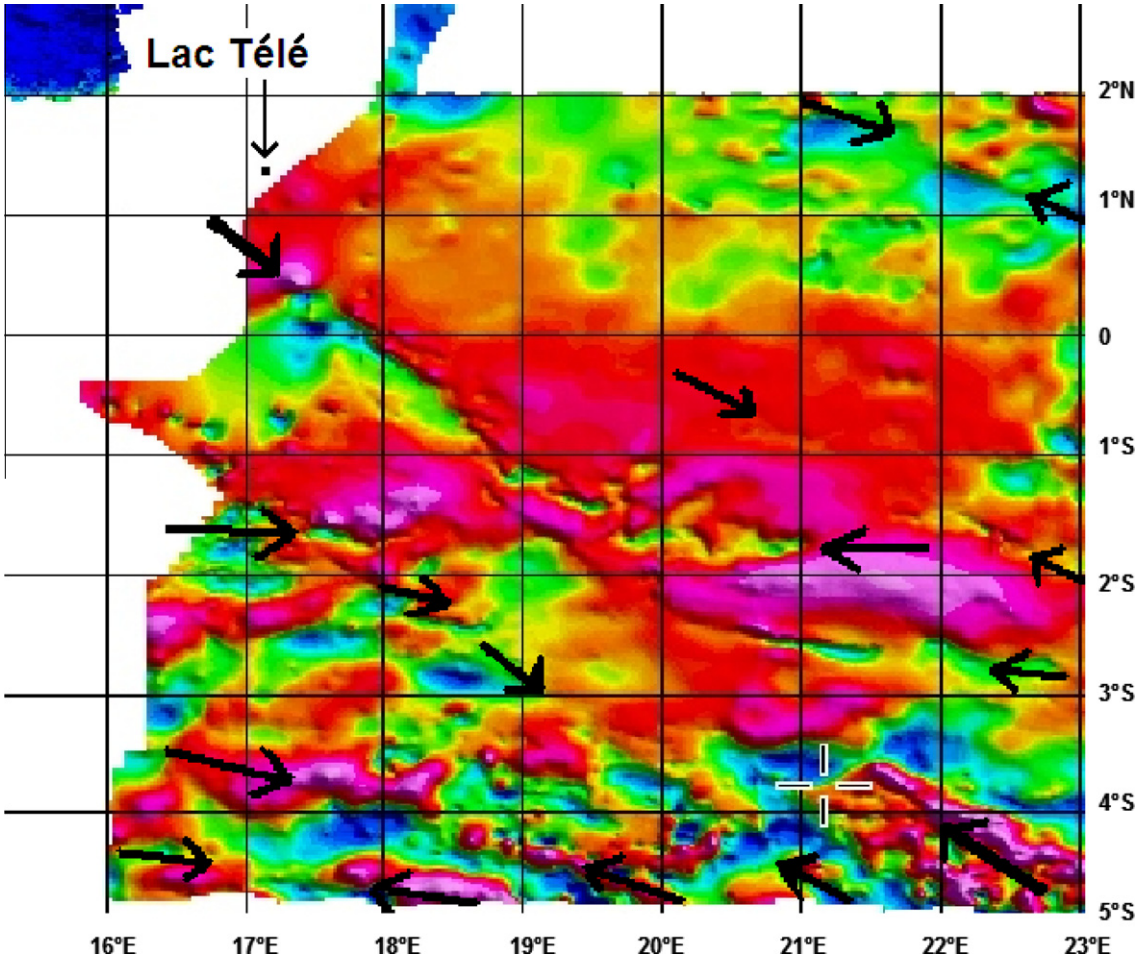

Fig. 7. Total field magnetic data of part of the Congo Basin, compiled from 1 × 1 km grid, by the African Magnetic Mapping Project at Leeds University (Reford and Kimun'a, 1993). Lineaments due to NW–SE and E–W structures are labelled by pairs of arrows facing each other. The Lac Télé structure is shown in an area not covered by the Leeds magnetic dataset. The lines of latitude and longitude shown are 1° apart. Image courtesy of Dr. C. Reeves.

diameter) and El'gygytgyn (18 km diameter) appear to lack obvious central uplifts- but this has been attributed to burial of central uplifts by sediments filling the surrounding moats in fast sedimentation-rate regimes (Koeberl et al., 2007; Gurov et al., 2007). Lac Télé, by contrast, is in an area of very low relief, and has a low sedimentation rate of 15 mm/century, based on the radiometric dating of Laraque et al. (1998).

(6) Presence of a magnetic anomaly in the N part of Lac Télé. The magnetic anomaly in the northern part of the structure fits a typical dipole anomaly, and was modelled as having been produced by a steeply-dipping magnetic body having dimensions of ~350 m in length downdip, and ~500 m wide (Laraque et al., 1997, 1998). Such anomalies are not characteristic of impact-produced magnetic signatures (Pilkington and Grieve, 1992), and the presence of such a magnetic anomaly in sedimentary rocks militates against an impact origin. The magnetic anomaly is most likely due to an intrusion, possibly a dyke following the trend of the NW–SE lineament going through Lac Télé. There are numerous NW–SE-trending high-amplitude linear magnetic anomalies, due to dykes, parallel to the Sangha horst, in the central Congo Basin (Fig. 7).

There remains the question of whether the lake could have been formed by a Tunguska-type atmospheric explosion. Laraque et al. (1998), despite their negative results in the search for iridium anomalies or other evidence for impact, suggested that the Lac Télé structure may have formed by a fireball of the Tunguska-type, caused by an impacting asteroid or comet exploding in the upper atmosphere. There have been several recent studies which have modeled the Tunguska event (Artemieva and Shuvalov, 2007; Collins et al., 2008, and references therein), which can be used to evaluate the feasibility of such an event producing the Lac Télé structure. According to the model of Artemieva and Shuvalov (2007), the Tunguska event was produced by a cosmic body entering the atmosphere and disintegrating and vaporising at a height of between 20 and 10 km. The vaporized material was buoyant and accelerated back up the wake, while a shock wave reached the ground and caused the well-known devastation of trees, without producing a crater (Collins et al., 2008). Thus, cosmic bodies such as asteroids or comets are either mechanically weak and break up in the upper atmosphere upon impact, or they are strong, and make it to the ground, where their kinetic energy excavates an impact crater. An atmospheric burst of the type postulated by Laraque et al. (1998) could not have produced a 4 m deep lake of the size of Lac Télé- at the most it would have devastated trees over a large area, by analogy with the Tunguska event (Collins et al., 2008), and the palynological evidence is against that (see below).

The absence of any known volcanism in the Congo Basin makes it unlikely that the Lac Télé structure is of volcanic origin. No volcanic rocks have been found in or around Lac Télé (Laraque et al.,

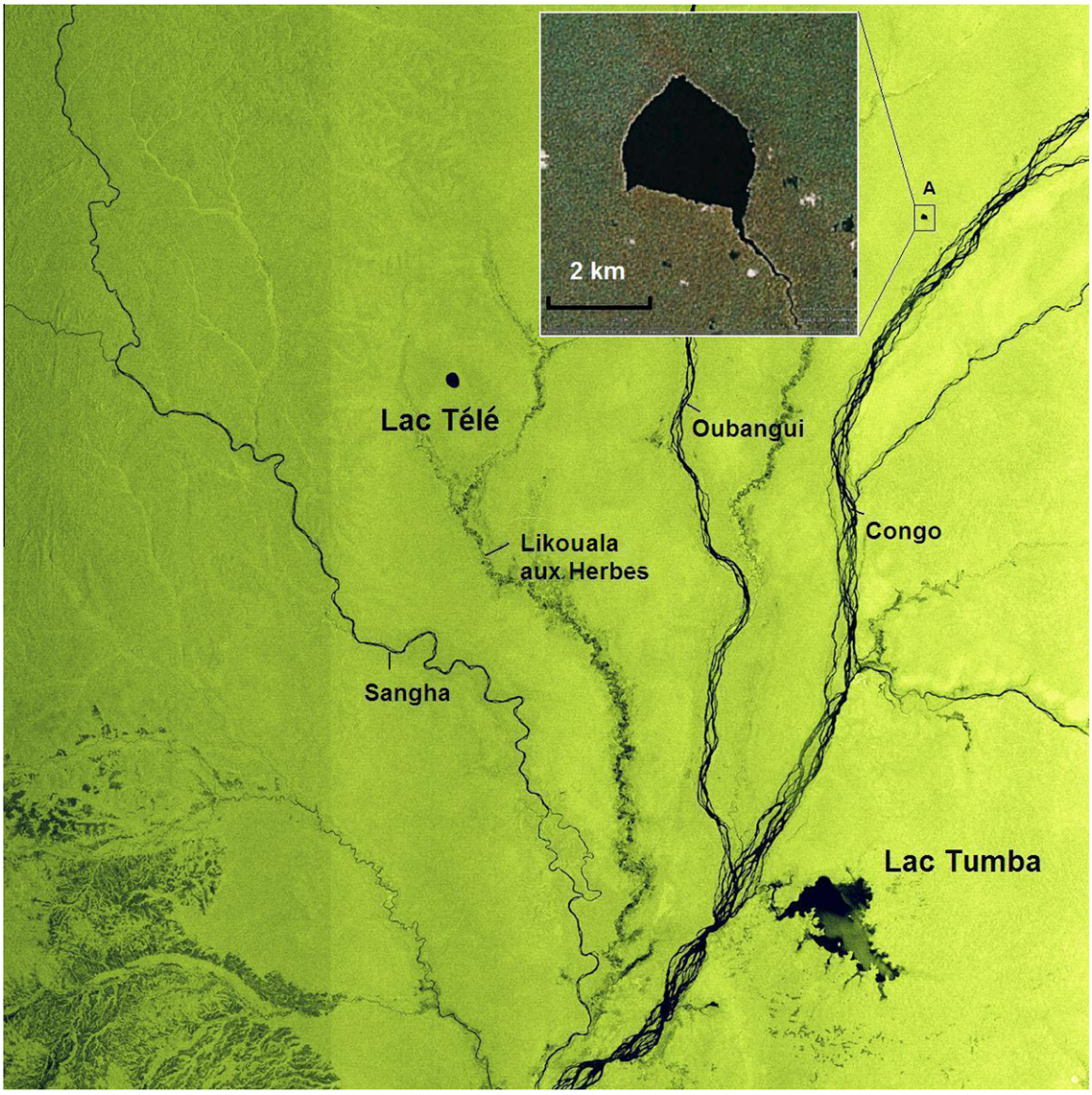

Fig. 8. Envisat ASAR Wide-Swath Radar Image (courtesy of European Space Agency) showing the rain forest region (artificially coloured) of the NW Congo Basin, with the Congo, Sangha and Likouala aux Herbes rivers, and the lakes Télé and Tumba. An isolated lake, north of the Congo river, numbered A, is shown enlarged in an inset. It has a solitary outlet which is a tributary to the Congo. Image: ASA_WSM_Orbit4441_20030105. The width of the image is ~320 km. See Fig. 1 for location.

1997, 1998). The stucture is also far too large to have been produced by a kimberlitic intrusion (an alternative hypothesis suggested for the Tunguska event of 1908; Kundt, 2007). It is larger than the largest known kimberlite pipe, Mirnyy (1.25 km diameter) (Dawson, 1980), by a factor of five. If it is of volcanic origin, the closest analogue would be with maarlike explosive vents. However, the flat-bottomed nature of the lake's structure is atypical of volcanic vents. Nevertheless, the presence of a magnetic anomaly in the N of the structure may indicate the presence of an igneous intrusion at depth, extending down to >300 m (Laraque et al., 1997, 1998).

The presence of NE-SW lineaments in the NW Congo basin suggests that the Sangha Horst, and its continuation in D.R. Congo, has undergone neotectonic reactivation, so that it can be seen even in the Neogene sediments and alluvium. The cause of such a reactivation may be far-field effects of the East African Rift System, which is currently tectonically active, and which has resulted in the reactivation of Mesoproterozoic Kibaran faults to produce the Upemba graben and horst system in the SE part of the Congo Basin (Robert, 1946; Sebagenzi, 1997). There is seismic evidence that the NW–SE-trending horst in the Congo Basin is neotectonically active. Graham and Brandt (1996) have recorded about a dozen intraplate seismic events, ranging in magnitude from 3 to 5 on the Richter scale, in the Congo Basin, which follow a linear trend along the strike of the central NW–SE horst. The two largest recorded events, of magnitude 5.5, are on either end of the Sangha Horst of NW Congo (Graham and Brandt, 1996; Ayele, 2002). Focal mechanisms calculated for these earthquakes indicate an E–W compression, giving rise to thrust movement, inferred to be from far-field intraplate compressional stresses arising from ridge-push forces in the Mid-Atlantic Ridge and the East African Rift System (Ayele, 2002). Neotectonic movements can cause blockage and damming of channels in river systems, forming extensive swamps and lakes, as has been demonstrated in the Okavango delta region (Modisi, 2000). Lac Mai Ndombe and Lac Tumba are shallow lakes similar to Lac Télé, in that although they have large surface areas, they are only 2–10 m deep, and they appear to have formed by damming of tributaries to the Congo river (Rainey et al., 2010; Stokes

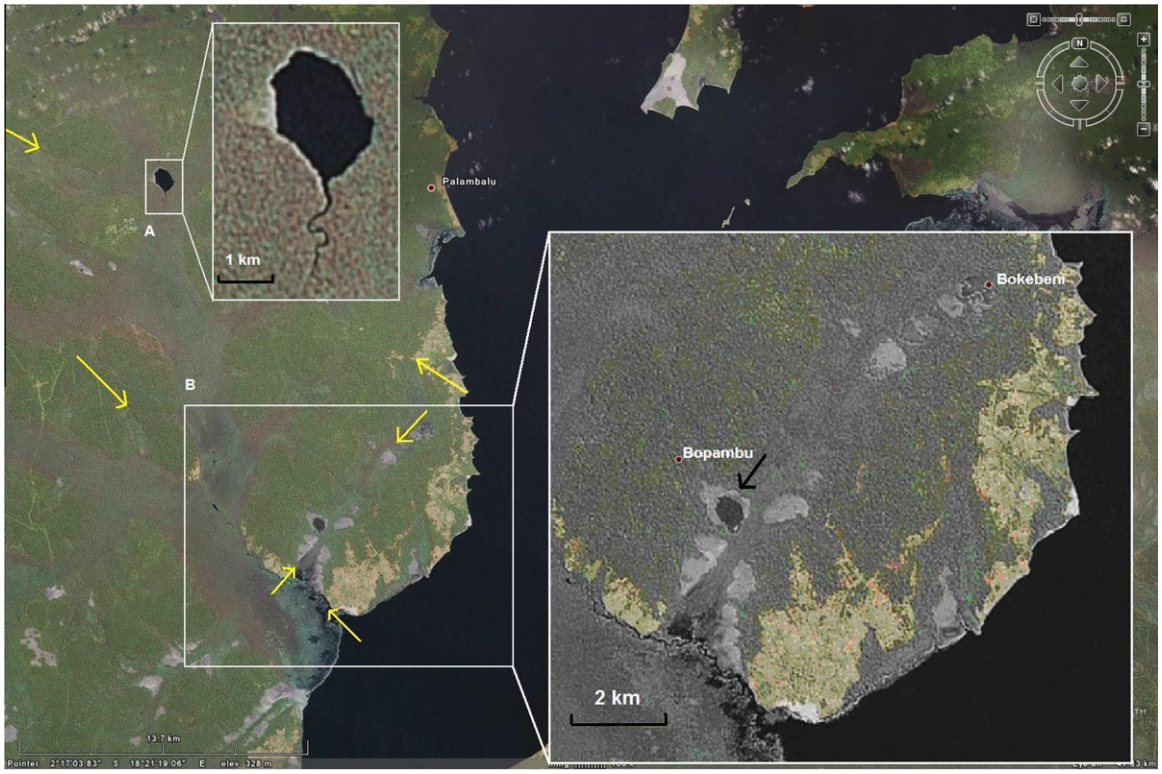

Fig. 9. Satellite image (from Google Earth) of the SW part Lac Mai-Ndombe, in the Congo Basin in western Democratic Republic of Congo (see Fig. 1 for location). Boxes labelled A and B are shown in close-up as insets. A. Isolated ~1 km diameter lake (centred on 18°10′36″E, 2°11′42″S) surrounded by unbroken rain forest, west of Lac Mai-Ndombe. A sinuous distributary channel issues from the south of the lake, and joins a SSE-flowing tributary of Lac Mai-Ndombe. B. Southwestern part of Lac Mai-Ndombe, showing a tributary which enters the lake in the west, flanked by former lakes (light grey colour) which appear to have silted up. Structural lineaments, shown up by straight river courses, are shown with yellow arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2010). Many of the tributaries of the Likouala aux Herbes and Sangha river systems show structurally-controlled straight segments (Fig. 4), which indicates a neotectonic control on drainage distribution. The Congo Basin has experienced significant epeirogenic movements which have drastically re-organized its hydrology, reversing the direction of the formerly east-flowing Congo river since the Miocene (Stankiewicz and de Wit, 2006). Along the southeastern flanks of the Congo Basin, rift-related tectonics in the Upemba graben has isolated drainage systems since the Plio-Pleistocene, resulting in vicariant speciation of lechwe species (Cotterill, 2005).

A clue to the origin of the Lac Télé structure comes from the description of the fringing vegetation along the lake perimeter. Laraque et al. (1997, 1998) suggested that the lake is getting smaller with time as the vegetation grows inward, like new skin growing over a healing wound. The basis of this analogy is the composition of the fringing vegetation in the past, reconstructed from a palynological study of the lake sediment. The pollen analysis shows that there has always been a marshy rain forest, with a predominance of trees such as *Symphonia globulifera*, *Uapaca*, *Hallea* and *Santiria*; and the consistency of strongly hydromorphic or lacustrine environments is indicated by the continuity of species such as *Pandanus* and *Alchornia*. However, the abundant presence also of *Macaranga*, which is a pollen produced in great quantity and is widely-dispersed, is characteristic of a dynamics of conquest or pioneer forest recolonization, which is usually related to man-made or natural perturbations of the rain forest environment (Laraque et al., 1997, 1998). The implications are that the lake could have been larger, and of a different shape, and has acquired its present shape due to choking by vegetation growth. In support of this one could cite the presence of other similar isolated lakes in the swamps of the Congo Basin. For example, there is another isolated lake in the northern part of the Democratic Republic of Congo (Fig. 8) which, although not ovoid or circular, resembles Lac Télé in many other respects. It is situated in the interfluve between the Oubangui and Congo rivers, in an unbroken area of tropical rain forest covering at least 7500 km^2. It has two straight fault-controlled edges, and a solitary outlet which flows into the Congo river. Another small isolated lake (A in Fig. 9) is situated some 13.5 km SW of Lake Mai-Ndombe, the largest lake in the Congo Basin. This small lake of about 2 km^2 area also resembles the other two isolated lakes in that it is surrounded by marshes, and has an outlet in the form of a small stream. It has been stable for several decades, since it is present in 1975 Landsat imagery (Short et al., 1975, p. 375), as well as in 2010 imagery accessible on Google Earth. This lake is situated adjacent to a NW–SE lineament, and may have been formed by blockage due to reactivation of this structure. Also in Fig. 9, several small former lakes flanking a linear, structurally-controlled NE-SW trending tributary of Lac Mai-Ndombe show evidence of having been larger, and of having choked up gradually from the periphery to the centre. One lake (arrowed) SE of the village of Bopambu, appears to be still occupied by open water in the centre, but is surrounded by an annulus of light grey material similar to that in the other former lakes. This shows that the former lakes were gradually infilled by material (vegetable matter and sediment?), starting from the periphery and moving towards the centres of the lakes.

5. Conclusions

The Lac Télé structure is located in the NW part of the intracratonic Congo Basin, in a region dominated by Holocene alluvium, dense tropical rain forest, and swamps. It is situated at the

intersection of NE–SW and NW–SE lineaments, which appear to be neotectonic features produced by reactivation of older structures. The NW–SE-trending lineament is part of a set of lineaments, mainly defined by straight second-order river segments, which parallel a large Neoproterozoic horst running through the centre of the Congo Basin, and which was recognised using geophysical techniques (Verbeek, 1962; Hydro-Congo, 1981; Daly et al., 1991, 1992).

Modelling of the Lac Télé as an impact structure, using the computer program of Collins et al. (2005), indicates a number of features which ought to be present: a complex impact structure with a final depth of 500 m and a diameter of 5.6 km in a sedimentary target, produced by an asteroid with density of 3000 kg m^{-3}, travelling at a typical velocity of 17 km s^{-1}, and impacting at an angle of 45°; an overturned rim, a continuous ejecta blanket for a radius of >10 km outwards from the centre of the structure. The absence of any of these features (complex structure, depth ~0.1 times the diameter, overturned rim, continuous ejecta blanket), coupled with the irregular ovoid shape, the palynological record indicating continuity of the same tropical forest and marsh environment for the past 6600 yrs, and the location of the structure at the intersection of major regional lineaments, are strong arguments against the impact hypothesis for the origin of the Lac Télé structure. There is no evidence for any young or active volcanism within a 950 km radius of the structure, hence a volcanic origin is extremely unlikely.

The Lac Télé structure as an isolated lake ecosystem is not unique in the Congo Basin, and there are several other small isolated lakes surrounded by rain forest and marshes, and from which small distributary channels radiate, similar to those issuing from Lac Télé. These kinds of isolated lake systems may be a hydrologic response to the blockage of channels in low gradient swamplands due to neotectonic activities resulting from far-field stress reactivation of old fault systems in the basement. Lac Télé and other similar lacustrine systems may be biodiversity hotspots because they acted as refugia (Maley, 1996; Cotterill, 2005) following hydrological re-organization of the Congo Basin due to neotectonic activities.

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